Spectral Implications of Variability in GRB Fireballs*

Ravi P. Pilla
Department of Physics, Columbia University, New York, NY 10027, USA;
ravi@cuphyb.phys.columbia.edu
Abraham Loeb
Astronomy Department, Harvard University
60 Garden Street, Cambridge, MA 02138, USA;
aloeb@cfa.harvard.edu

Cosmological γ-ray bursts originate from relativistic winds. Temporal fluctuations in the wind velocity can give rise to internal shocks which dissipate a significant fraction of the wind kinetic energy. Part of the energy dissipated is transferred to the electrons through Fermi acceleration. If the post shock fluid is strongly magnetized, the relativistic electrons cool initially through synchrotron emission, and later through Compton scattering. The upsacttered radiation triggers a cascade of e^+e^--pairs. We compute the final spectrum for a wide range of parameter values for the emission region. We show that the spectral diversity observed by BATSE can be naturally explained by emission from internal shocks, which are associated with the observed source variability.

1 Introduction

The origin of γ-ray bursts (GRBs) is still unknown. However, independent of the energy source, the GRB emission itself must come from a highly relativistic wind. If most of the wind energy is carried originally in the form of proton kinetic energy [1], one needs to identify a process which would convert part of this energy into non-thermal γ-rays, after the expanding wind had already become optically thin. On the basis of the observed temporal fluctuations in the burst data, it has been suggested that the burst emission is actually produced through *internal shocks* in the expanding wind [2]. In this model the central source is compact ($\sim 10^{6-7}$ cm) and emits a relativistic wind of total energy $\approx 10^{52}$ erg over a time $t_d \lesssim 10^2$ seconds, with negligible mass of entrained protons ($\lesssim 10^{28}$ g). Strong temporal fluctuations in the luminosity of the source produce many thin layers of $e^+e^-\gamma$-plasma, or fireball shells, with a varying specific energy per unit baryonic mass. These shells acquire different Lorentz factors, and therefore tend to collide at a larger radius, thus producing (internal) shock waves. The temporal behavior of the bursts produced by multiple shell-collisions has been studied recently [2]. Here we report some results on the spectra from such collisions; more details of this calculation will be given elsewhere [3].

2 Radiation Mechanisms and Burst Spectra

Consider two fireball shells of energy $\widetilde{\varepsilon}_i$ and rest mass m_i ($i = 1, 2$) starting from the same initial radius. After an initial acceleration phase, the shells reach Lorentz factors $\widetilde{\gamma}_i \approx \widetilde{\varepsilon}_i/m_i c^2$, where c is the speed of light in vacuum; we take $\alpha \equiv \widetilde{\gamma}_2/\widetilde{\gamma}_1 > 1$. If the second shell is released behind the first one after a time

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t_{var} (typical variability time) in the observer frame (or the rest frame of the central source) the two shells will collide at an observer-frame radius $r_c = 2ct_{var}\widetilde{\gamma}_1^2\alpha^2/(\alpha^2 - 1)$ and move with a common Lorentz factor

$$\widetilde{\gamma} = [\widetilde{\gamma}_1\widetilde{\gamma}_2(\widetilde{\varepsilon}_1 + \widetilde{\varepsilon}_2)/(m_1\widetilde{\gamma}_2 + m_2\widetilde{\gamma}_1)c^2]^{1/2}. \quad (1)$$

The total energy dissipated in the collision, $\widetilde{\varepsilon}_d$, defines the dissipation efficiency

$$\xi_d \equiv \widetilde{\varepsilon}_d/(\widetilde{\varepsilon}_1 + \widetilde{\varepsilon}_2) = 1 - [\delta_\varepsilon(1+\delta_m)^2/(1+\delta_\varepsilon)(\delta_\varepsilon + \delta_m^2)]^{1/2}, \quad (2)$$

which depends only on the ratios $\delta_\varepsilon = \widetilde{\varepsilon}_2/\widetilde{\varepsilon}_1$ and $\delta_m = m_2/m_1$. For $\delta_{\varepsilon,m} \sim$ a

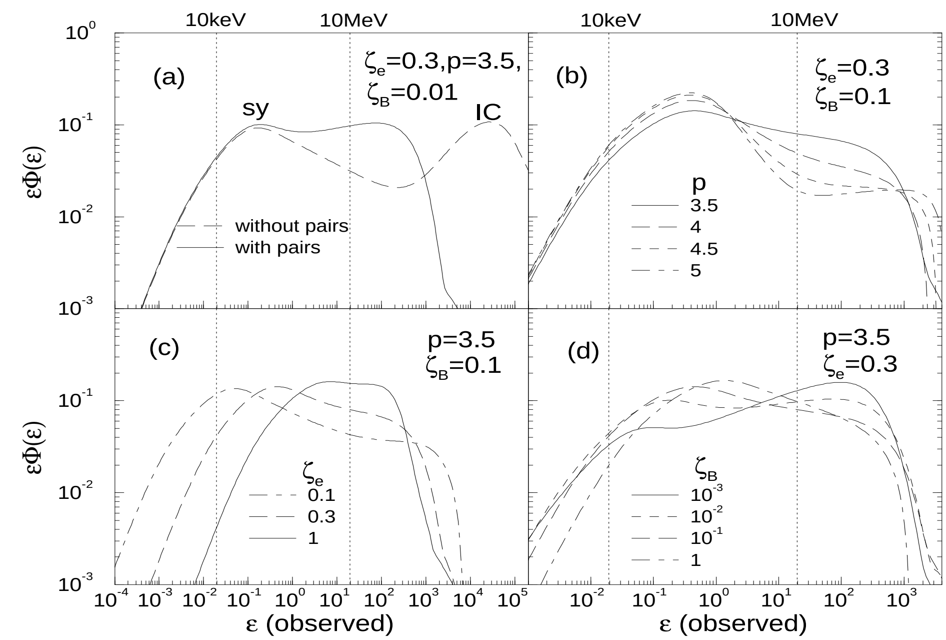

Figure 1: Spectra from internal shocks for physical conditions of the source given in the text and the conditions in the emitting region specified on each panel. Panel (a) compares the spectrum before (with synchrotron [sy] and inverse-Compton [IC] peaks marked) and after the pair cascade. Panels (b)-(d) show the dependence of the final spectrum on p, ζ_e, and ζ_B, respectively. The results are very sensitive to the value of ζ_e. There is no simple relation between the Fermi index p and the shape of the spectrum in the BATSE band (marked by the vertical dotted lines on each panel).

few, $\zeta_d \gtrsim 10\%$ can be achieved [2]. The shock waves heat the protons to an average comoving Lorentz factor $\overline{\gamma}_p \simeq 1 + \xi_d\widetilde{\gamma}_1(1+\delta_\varepsilon)/\widetilde{\gamma}(1+\delta_m)$; the protons subsequently transfer a fraction ζ_e of their kinetic energy to the electrons through Fermi acceleration. This transfer of energy is expected to be rapid [3].

As an example for the typical physical properties of the emission (post-shock) region, we take a bulk Lorentz factor of $\widetilde{\gamma} \approx 400$, proper density of baryons $n \approx 1.1 \times 10^{12}$ cm^{-3}, comoving thickness $\Delta \approx 4.1 \times 10^{10}$ cm, and $\overline{\gamma}_p \approx 3$. With a radiative efficiency of $\sim 100\%$, these parameters correspond to a total observed

fluence of $\sim 3\times10^{-7}$ erg/cm^2 for a source redshift $z_s \approx 1$. Before electron cooling starts, the number of electrons per unit energy with a Lorentz factor γ is assumed to be proportional to γ^{-p}, where p is the Fermi-acceleration index; at that time, the average value of γ is $\overline{\gamma}_0 \approx 3.6\times10^3\zeta_e$. A magnetic equi-partition fraction ζ_B corresponds to a field strength of $B \approx 4.7\zeta_B^{1/2}10^4$ G. We denote the observer-frame energy of a photon in units of electron rest mass by ε, and the fraction of total radiation energy carried by photons in the interval $(\varepsilon, \varepsilon + d\varepsilon)$ by $\Phi(\varepsilon)$, so that $\int_0^\infty \Phi(\varepsilon)d\varepsilon = 1$. The values of p, ζ_B, and ζ_e are free parameters that might vary among different bursts.

Very high-energy photons are produced as the electrons cool via synchrotron emission and inverse-Compton scattering on a comoving time scale $t_c \sim 1/cn\sigma_T\overline{\gamma}_0^2$, where σ_T is Thomson cross section. Those photons remain in the wind for a time $\sim t_0 \equiv \Delta/c \gg t_c$, and produce relativistic e^+e^- pairs which immediately transfer their energy back to the radiation through Compton cooling. Such a cascade of pair creation and cooling leaves pronounced signatures on the emergent spectrum. The final spectra are shown in Figure 1 for a variety of values for p, ζ_B, and ζ_e. The additional dependence of the resulting spectra on r and $\widetilde{\gamma}$ can be found in [3]. The large variety of possible burst spectra might be responsible for the spectral diversity of bursts observed by BATSE [4].

3 Conclusions

We have shown that diverse spectra over a wide range of energies, covering that of BATSE, is a generic outcome of internal shocks produced by variability in GRB fireballs. The results shown here only pertain to the collision of a pair of shells but the qualitative spectral behavior of the entire event is likely to be similar.

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